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GIROMILL WIND TUNNEL TEST AND ANALYSIS VOLUME I - EXECUTIVE SUMMARY

Final Report for the
Period June 1976 - Oct 1977

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PROJECT SUMMARY

This project was conducted for the United States Energy Research and Development Administration (ERDA)under ERDA contract E(11-1)-3617 by the McDonnell Aircraft Company (MCAIR), a division of the McDonnell Douglas Corporation, P.O. Box 516, St. Louis, Missouri, 63166.

The feasibility of the Giromill as a viable wind energy conversion system was verified by the initial one year feasibility study completed in May 1976. That study concentrated on identifying the potential advantages of problem areas of the Giromill, and defining its cost effectiveness for comparison to more conventional systems being studied elsewhere. The initial emphasis of the study during the first six months was directed towards a parametric evaluation of the Giromill system. The results of this evaluation provided an understanding of the Giromill system and identified the major cost components. The latter part of the study was devoted to a more detailed investigation and cost optimization of the most promising Giromill system and preparation of a wind tunnel test plan. The results from that one year study have verified the Giromill feasibility and its cost effectiveness such that further effort to verify the theoretical performance was warranted.

The study described herein is a continuation of the Giromill investigation in which a wind tunnel test of a model Giromill rotor was performed. The primary objective of the wind tunnel test was to obtain data for comparison with the Larsen cyclogiro vortex theory program employed for predicting the Giromill performance.

The model had a rotor diameter of 7 ft. (2.13 meters) and a solidity (total blade area divided by rotor span times diameter) of 0.3. This was achieved by a three bladed rotor having blade chords of 8.4 in. (21.3 cm) and a span of 5 ft. (1.52 meters). The blades were modulated by use of replaceable cams, that simulated the various operating conditions, and a push rod arrangement connected to a bellcrank about the blade pivot point. Rotor RPM control was achieved with an electric motor/generator that could be used to either drive the rotor or absorb the rotor power to maintain RPM. A torque meter measured the rotor shaft torque, and together with the RPM was used to measure the power of the rotor.

Due to the importance of accurate velocity measurement on the measured performance, and due to the low velocities necessary for this test, two independent velocity measurement systems were used; the standard pitot-static tunnel

system and a hot film anemometer system. These two systems differed by approximately 11% during the test with the hot film velocity being the lower. This difference has not be resolved. The best overall agreement with predicted performance was achieved using the pitot-static system to reduce the data but credible evidence also exists to support the higher performance based on the hot film velocity.

Until the higher performance is verified by future tests, the Larsen Cyclogiro vortex theory program, with the rotation rate correction, will be used to predict performance.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1. Overview

The feasibility of the Giromill as a viable wind energy conversion system was verified by the initial one year feasibility study completed in May 1976 and reported in References 1 and 2. This report summarizes the design, fabrication and testing of a Giromill model in a wind tunnel. The primary objective of the test was to verify that the computed performance (Larsen cyclogiro theory) was obtainable. A secondary objective was to obtain a comparison of Giromill performance with that of other types of vertical axis machines.

2. Wind Tunnel Model

A picture of the model installed in the MCAIR mini-speed wind tunnel is shown in Figure 1. A drawing of the Giromill showing more detail is presented in Figure 2. The three bladed wind tunnel model rotor had a diameter of 2.1 meters (7 ft) and a blade span (height) of 1.5 meters (5 ft). The blade chord was 21 cm. (8.4 inches) providing a solidity, σ, of 0.3 (total blade area divided by rotor span times diameter). The mini-speed tunnel has a 4.6 m (15 ft) wide by 6.1 m (20 ft) high open jet test section.

The Giromill blades were modulated by a push rod which was recessed within the lower blade support arm and connected to a bellcrank about the blade pivot point as detailed in Figure 3. The blade modulation profile was obtained by a cam and cam follower connected to the push rod. Replaceable cams provided desired blade modulation at the various operating points. Various operating conditions were achieved by adjusting the rotor RPM and the tunnel speed. Rotor RPM was controlled with an electric motor/generator that could either drive the rotor or absorb rotor power in a light bank to maintain the RPM. This RPM control system was used by Sandia Lab in their Darrieus rotor test reported in Reference 3. A torque meter measured the rotor torque and together with the RPM provided the rotor power. Tunnel velocity was measured by a hot film anemometer probe, mounted above and forward of the rotor, and also by the normal tunnel pitot static system. Hot film anemometer probe velocity is hereinafter referred to as V_P and the tunnel pitot static data velocity as V_T. The rotor control and data acquisition system is shown schematically in Figure 4. The outline of the tunnel, Giromill rotor, and probe positions are drawn to scale in this figure.

3. Test Technique

The test was conducted by initially bringing the rotor RPM up to the desired speed, 100 RPM for Giromill mode tests and 120 RPM for Darrieus mode tests, and then setting the tunnel velocity V_T to obtain the test blade speed ratio, λ. When conditions

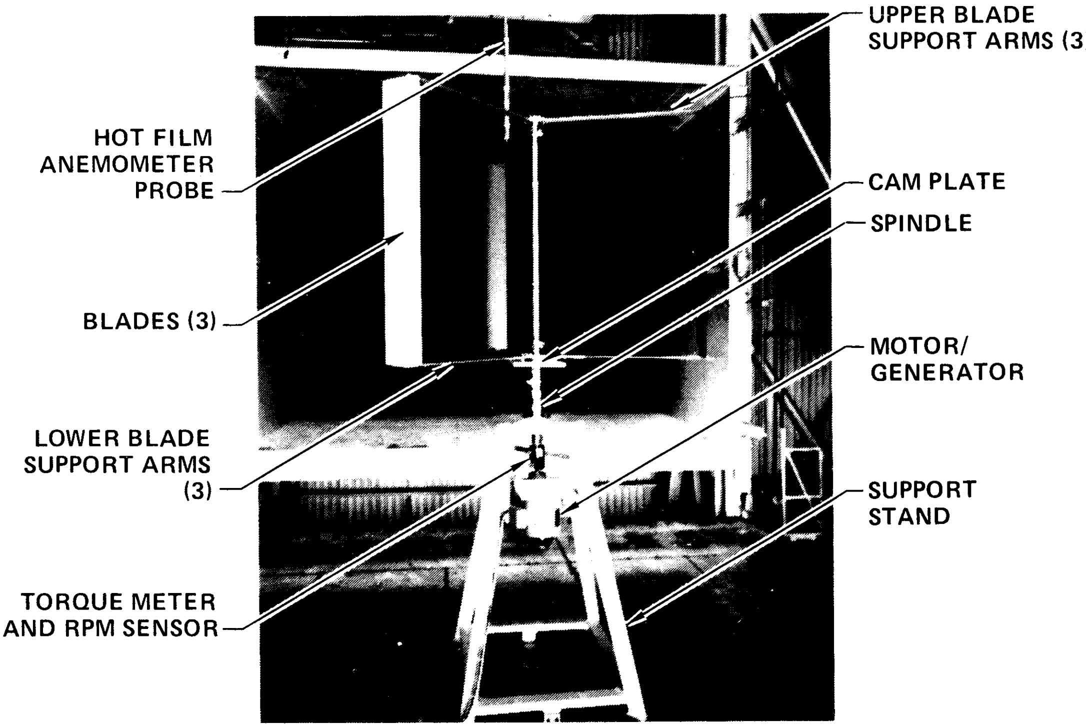

FIGURE 1
GIROMILL MODEL INSTALLATION

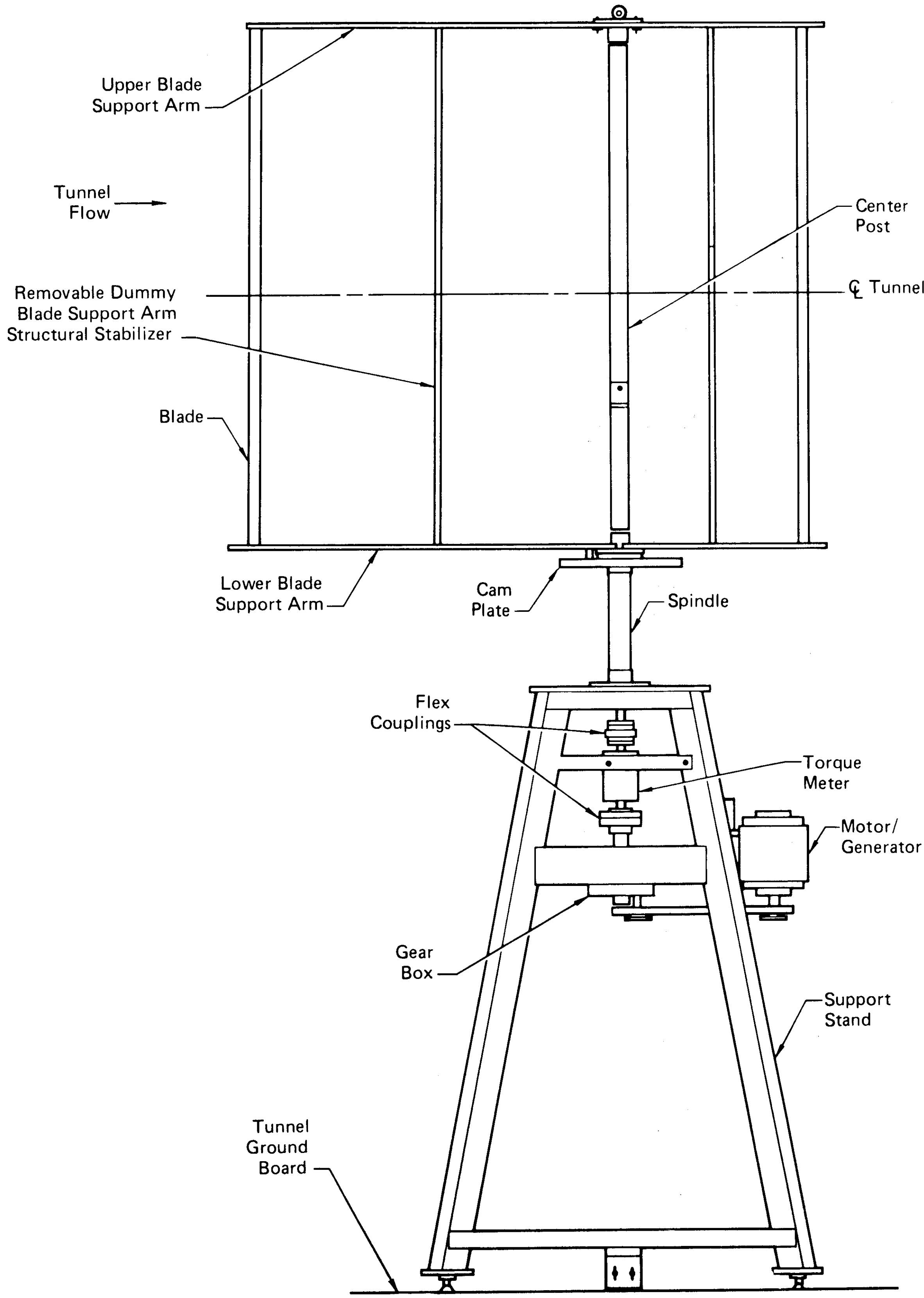

FIGURE 2
GIROMILL MODEL INSTALLATION

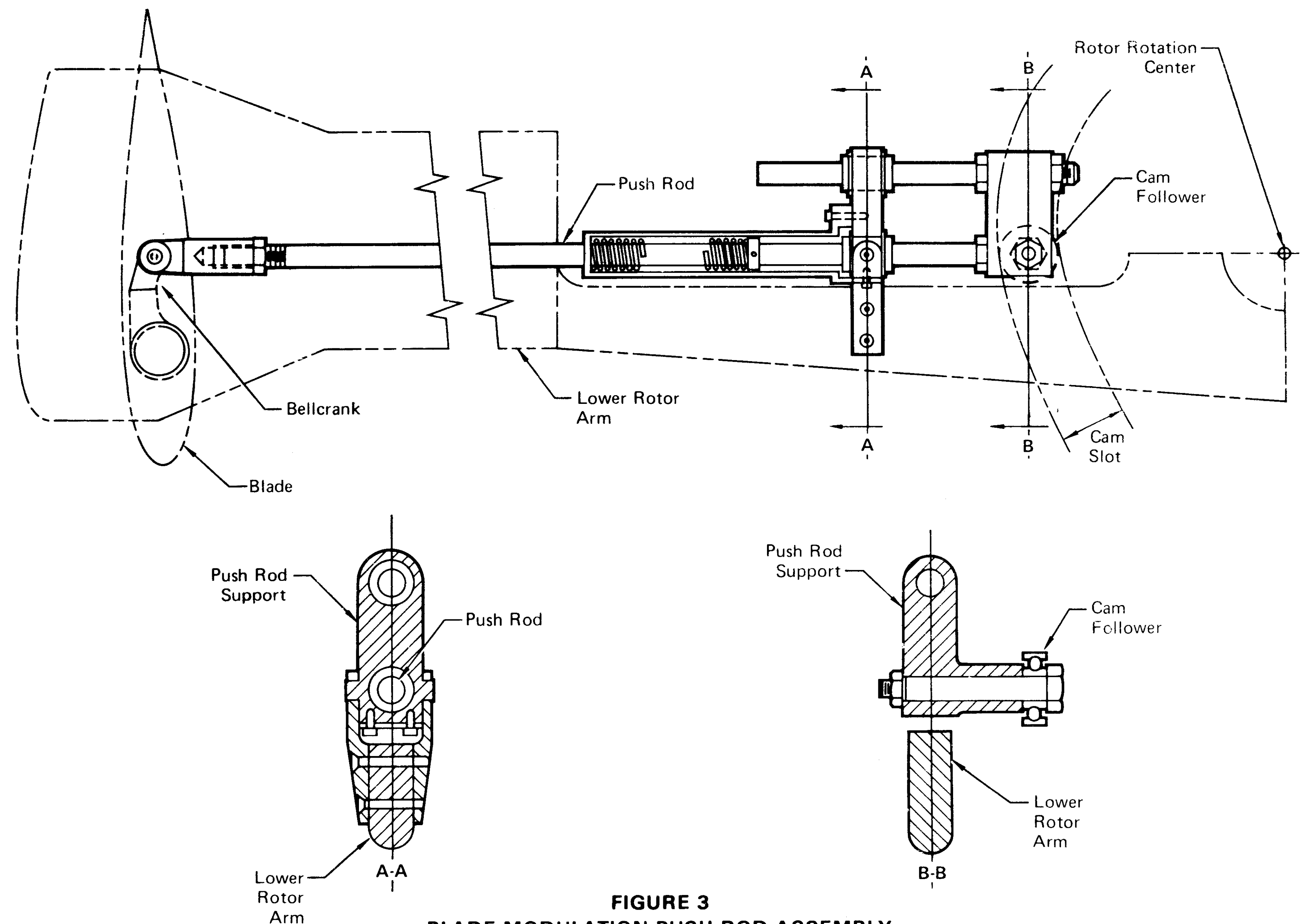

FIGURE 3
BLADE MODULATION PUSH ROD ASSEMBLY

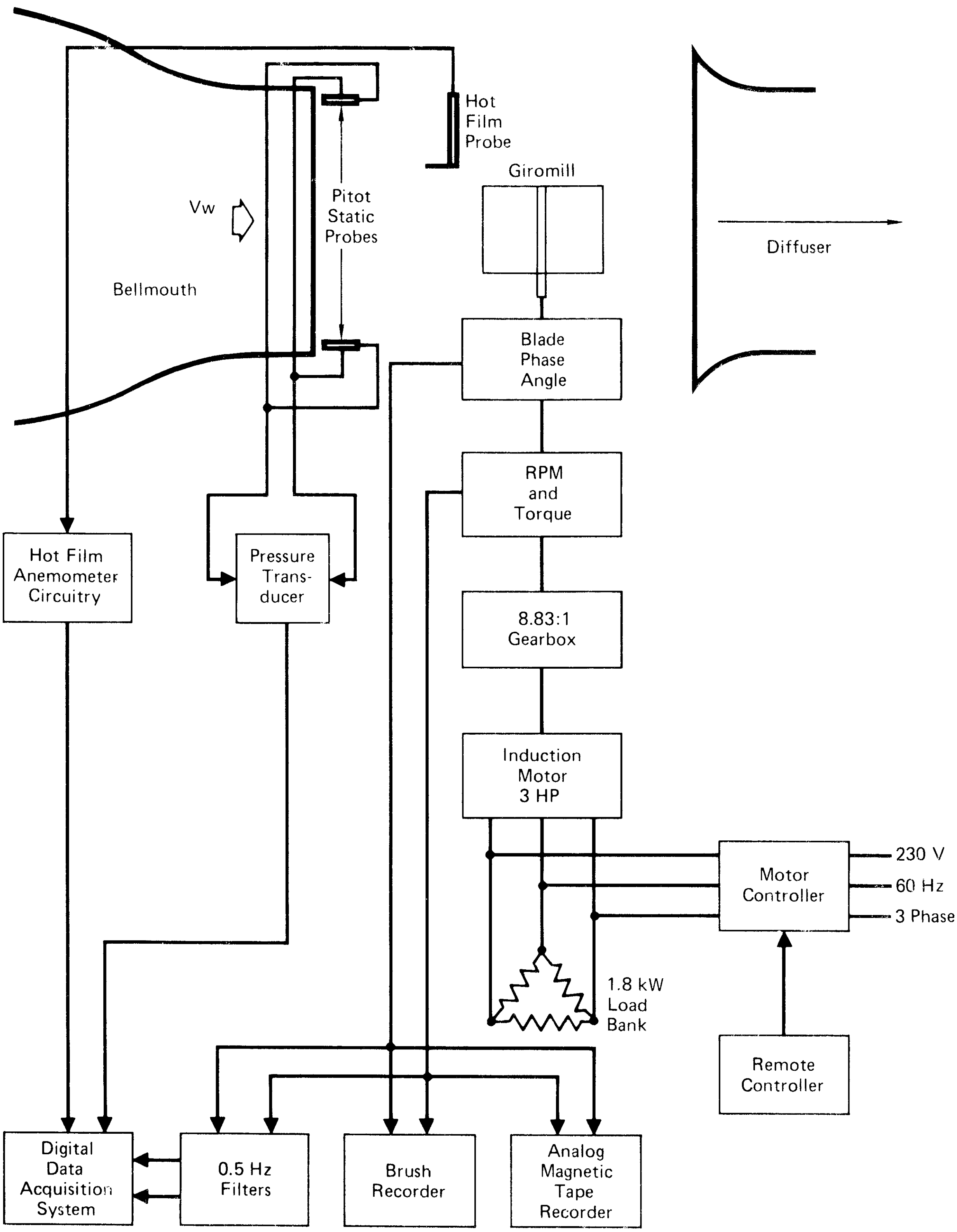

FIGURE 4
ROTOR CONTROL AND DATA ACQUISITION SCHEMATIC

were stabilized, two separate 2-second spans of filtered digital readouts of RPM and torque, along with the two tunnel velocity sensors, were taken at 10 samples per second and recorded (40 data points for each parameter). For the Giromill mode tests, rotor RPM was then changed by approximately ± 5 RPM and data again recorded. This was done to obtain test points about the nominal blade speed ratio for each blade modulation profile cam tested. Unfiltered analog tape data was also collected.

4. Test Results

As previously mentioned, tunnel velocity was determined by two independent methods. Unfortunately, the two tunnel velocity measuring systems did not agree as well as expected. V_p was consistently lower than V_T. The difference was at most 2 ft/sec which, for the low velocities used, amounted to about an 11% velocity difference. Careful scrutiny of both systems failed to conclusively pinpoint the reason for the discrepancy. Valid reasons for using either one can be presented. In any event, the data was reduced using both velocities.

Figures 5 and 6 present Giromill mode plots of power coefficient, C_p, versus blade speed ratio, λ, reduced using V_p and V_T, respectively. Each similar symbol group of data points were obtained with a specific cam profile as previously described. The estimated maximum performance envelope based on the test points is also shown. The data provides the aerodynamic performance of the test Giromill. It accounts for the parasite drag of the rotor system, but bearing friction of the shaft, push rods, and cam follower (obtained from wind-off tare runs) has been subtracted. The data therefore is comparable to that obtained by the Larsen cyclogiro vortex theory program assuming the dynamic effects of pitch rate are accounted for.

The comparison of the test envelopes with the theoretically computed envelope is shown in Figure 7. The upper theoretical curve is obtained from the Larsen cyclogiro vortex theory program assuming only static aerodynamic characteristics. In the actual case, however, the blade has a pitch rate equal to the sum of the rotor rotation rate ω, and blade modulation rate, $\dot{\theta}$. The blade therefore experiences additional forces and moments that are inherent in the test data, but must be accounted for in the theoretical estimates. The possible significance of pitch rate, which is not computed in the vortex theory calculations, was pointed out by Professor Robert E. Wilson from Oregon State University. A simplified correction was derived, which when applied, lowers the theoretically computed C_p envelope to that shown in Figure 7. This is very close to that achieved if V_T is

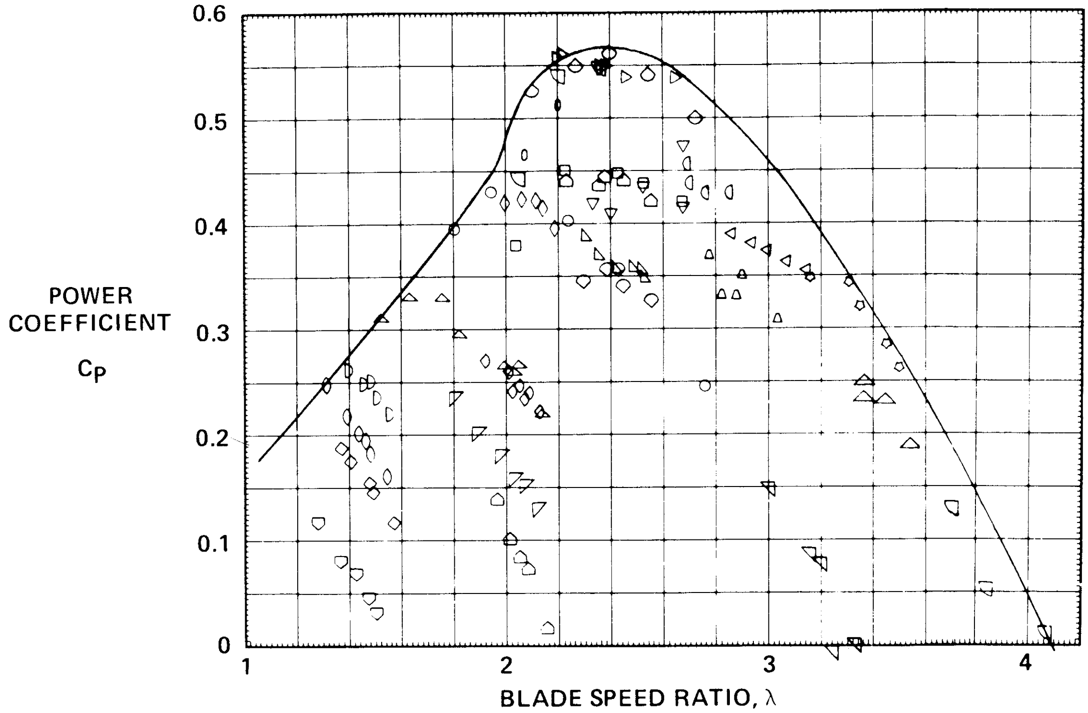

FIGURE 5
GIROMILL WIND TUNNEL TEST MODEL PERFORMANCE ENVELOPE
Normalized Using Hot Film Anemometer Velocity

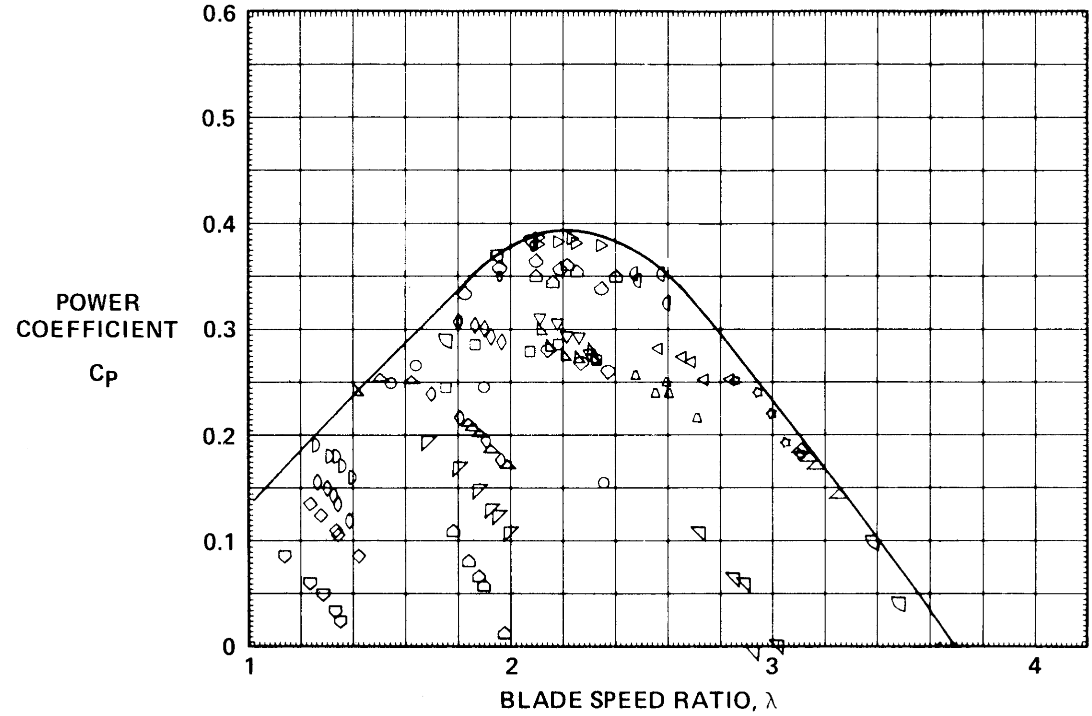

FIGURE 6
GIROMILL WIND TUNNEL TEST MODEL PERFORMANCE ENVELOPE
Normalized Using Tunnel System Velocity

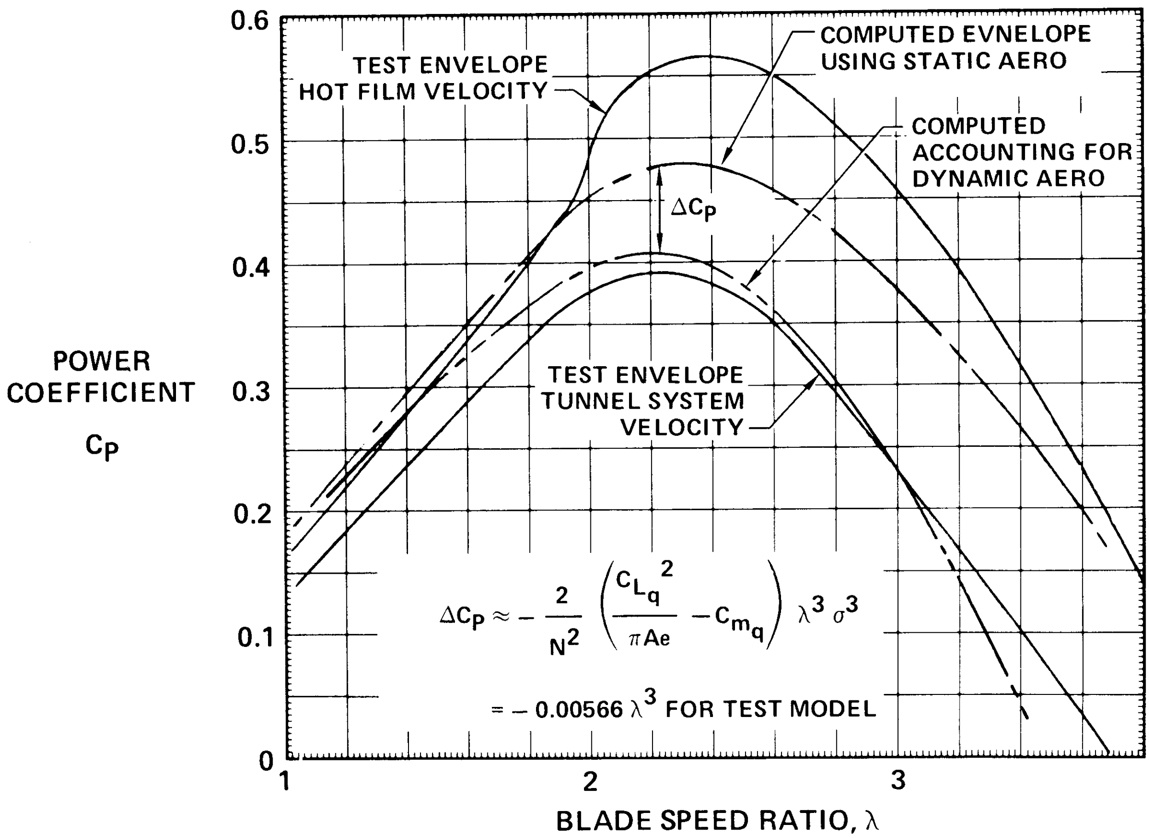

FIGURE 7
COMPARISON OF COMPUTED AND TEST GIROMILL PERFORMANCE ENVELOPES

used for the test data analysis. If the rotor rotation rate ω is much greater than $\dot{\theta}$ (which is cyclic and therefore has an average of zero), and using the average blade velocity ($V_{ave} = \omega R$, rotor rotation rate times rotor radius), the C_p correction for dynamic aerodynamic effects can be expressed as:

$$\Delta C_p = -\frac{2}{N^2}\left(\frac{C_{L_q}^{\ 2}}{\pi A e} - C_{M_q}\right)\lambda^3 \sigma^3 \qquad (1)$$

where N is the number of blades

C_{Lq} and C_{Mq} are the dynamic derivatives

A is the blade aspect ratio

e is the blade aerodynamic efficiency factor

From Reference 4 the values for C_{L_q} and C_{M_q} for the model rotor blade are

$$C_{Mq} = -.53$$
$$C_{Lq} = -3.0$$

Equation (1) for the wind tunnel model then becomes

$$\Delta C_p = -.00566\ \lambda^3$$

Note that the correction is a strong factor of both λ and σ. The smaller the σ, the smaller the ΔC_p correction, even though the operating λ range increases as σ decreases. The small ΔC_p correction is one advantage of using low rotor solidities.

Figures 8 and 9 present the data for the Darrieus mode tests and the modified Darrieus mode where the blades are flipped 3°. The plots are again normalized by V_p and V_T, respectively. The predicted Darrieus performance for the model rotor was obtained from Professor Robert E. Wilson, Oregon State University. This prediction was then corrected for ΔC_p.

It is evident that the Darrieus mode test data did not follow the predicted curve. The maximum C_p value is approached by the test data based on V_p, however, the shape of the curve is quite different. Also, the modified Darrieus with the $\mp$ 3° flip, that flips the blades in a manner that reduces the effective angle of attack, shows a substantial C_p increase over the Darrieus mode. This is due to reducing the rotor orbit region in which the blade is stalled. This trend in C_p with blade flip is consistent with the Giromill blade modulation which keeps the blade from stalling around the entire rotor orbit.

It is not surprising that the predicted Darrieus performance does not compare well with the wind tunnel results at the lower λ's. An accurate estimate for the

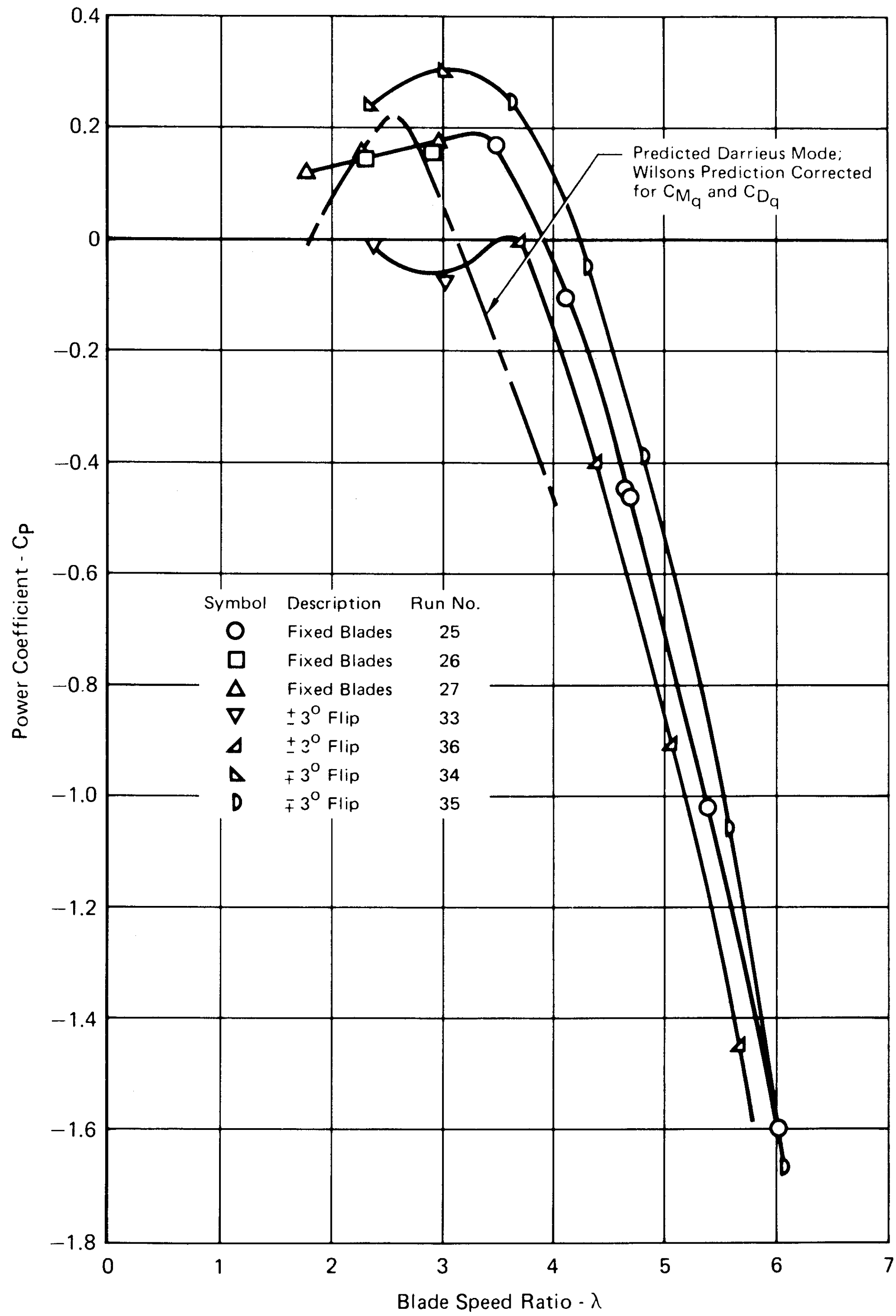

FIGURE 8
DARRIEUS MODE
POWER COEFFICIENT VARIATION WITH BLADE SPEED RATIO
Based on Hot Film Velocity

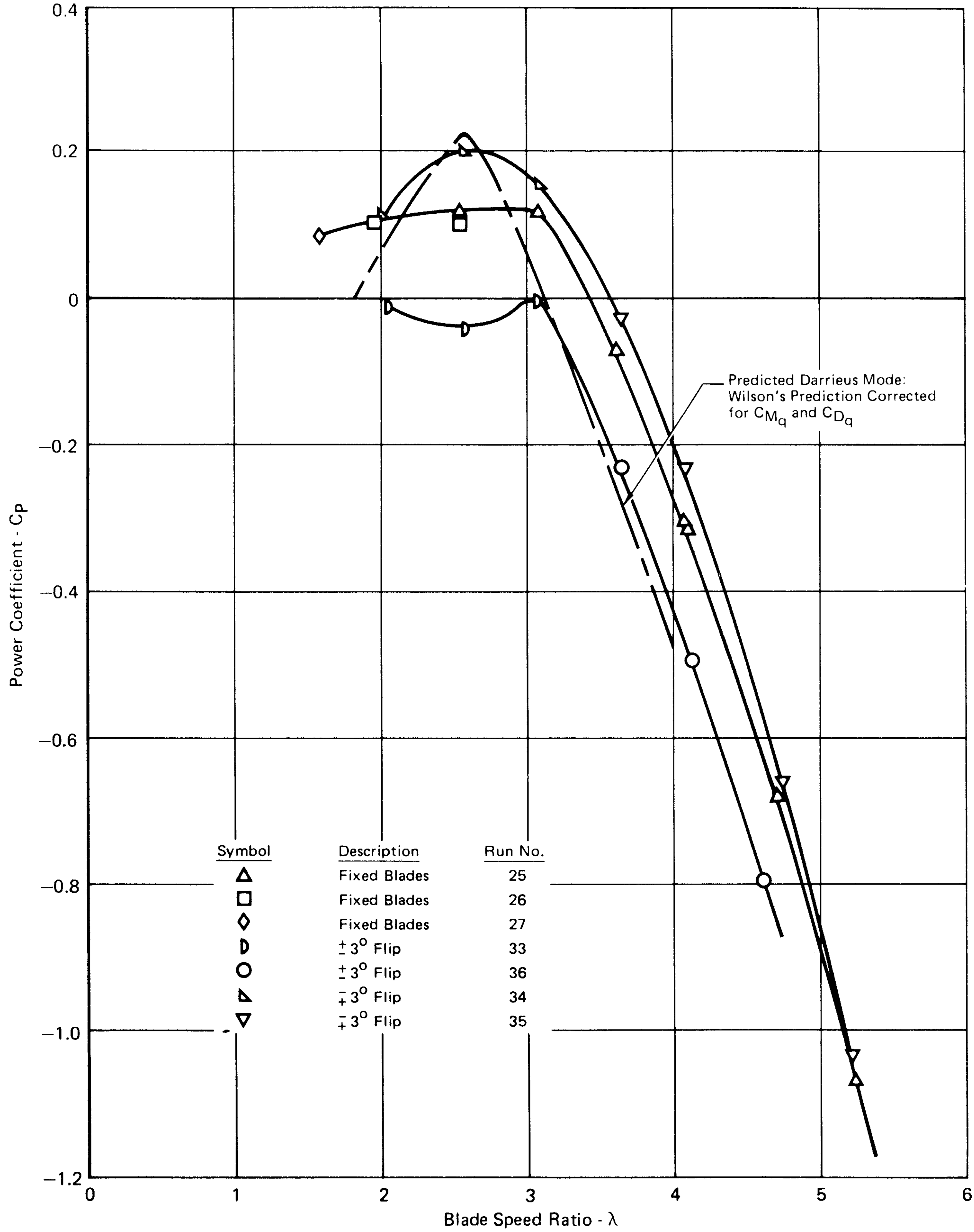

FIGURE 9
DARRIEUS MODE
POWER COEFFICIENT VARIATION WITH BLADE SPEED RATIO
Based on Pitot-Static Velocity

stall angle of attack and the lift and drag characteristics above stall are critical in the performance prediction at λ's where stall occurs. These characteristics are difficult to predict, especially under conditions of time varying angle of attack and Reynolds number. Also, an accurate calculation of the rotor induced flowfield is required since that in turn determines the blade angle of attack. The flow field approximations used in Wilson's analysis of the Darrieus are described in Reference 5. Additionally, the values of C_{M_q} and C_{L_q} used to correct for rotation rate effects were derived based on unstalled linear aerodynamic characteristics which can be quite different, even of opposite sign, in the stall regime.

5. Conclusions

The results of this test and analysis shows that the Giromill has good performance, equal to or much better than that predicted by the Larsen cyclogiro vortex theory when corrected for the dynamic aerodynamic effects. In future Giromill efforts we propose to use the Larsen vortex theory predictions (corrected) until other tests verify that we do indeed obtain the higher C_p values. For Reynolds numbers and solidities associated with full scale Giromills, maximum Cp values are predicted that are higher than that attained with the wind tunnel model. For a Giromill 60 ft. (18.3m) in diameter, with blades 30 ft. (9.1m) in span having an aspect ratio of 12, and with a solidity of .125, a maximum Cp of .54 is estimated.

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